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CASE STUDY

Analysis of the application of recycled polypropylene: a case study in the refrigeration segment in south of Brazil

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ABSTRACT

Goal: Analyze the benefits of the application of recycled polypropylene in the evaporation tray of refrigerators in a multinational company of electro-electronic equipment.

Design / Methodology / Approach: This research conducts a systematic literature review; performs a Life Cycle Analysis (LCA) of the polypropylene production, interpreting its results through a Pareto Diagram; and presents a case study in a multinational company of white line electro-electronic equipment.

Results: The LCA results point out that propylene and the components released by the chemical plant cause the main negative externalities under the environment and human health, so that during PP production, propylene is responsible for 72% of the impacts under global warming and 86% in the face of scarcity of fossil resources. Thus, the case study proposes recycling polypropylene, following the Circular Economy guidelines by aligning the proposal with the Zero Waste policy, with modular design, with Reverse Logistics, and with Sustainable Development Goals.

Research limitations: The work presents limitations inherent to literature review works, where filters are used to limit the search (limited to articles, published between 2012 and 2021 and written in English).

Practical implications: The research encourages recycling, pointing out its contribution under the environmental, social and economic spheres.

Originality / Value: The research presents originality and methodological value by combining qualitative and quantitative methods, and a theoretical and practical approach. Thus, it was possible to implement the research in the multinational company analyzed, and to measure the benefits obtained.

Keywords: Circular Economy; Life Cycle Analysis; Recycled Polypropylene; Refrigerator.

INTRODUCTION

The intensification of industrial activities, added to the development paradigm based on linear economy, makes the approach about sustainability become one of the biggest drivers of market changes (Fargnoli et al., 2018). Thus, by integrating sustainable development principles with the corporate business strategy, there is an element capable of increasing competitiveness in the supply chain (Vacchi et al., 2021), where the Circular Economy

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represents an approach that, when incorporated into the production chain, offers benefits under the environmental, social and economic spheres (Kohlbeck et al., 2021).

However, several gaps hinder the broad application of measures aligned with sustainable development, among them the difficulty in carrying out solid waste management (La Fuente, Tribst and Augusto, 2022). UNESCO highlights that if the population continues to grow at current rates, this will lead to a 20% increase in oil consumption (the basis for polymer production) by 2050, and if waste management practices do not improve by this date, there will be about 12 billion tons of plastic waste in the environment (UNESCO, 2021). Although there is legislation enacted for the correct management of solid waste in Brazil, such as the National Solid Waste Policy (PNRS) (BRASIL, 2010), there are several difficulties facing its application, being a multifaceted problem, which must be addressed from different perspectives (La Fuente, Tribst and Augusto, 2022).

Despite the legislative support, in Brazil only 1.3% of plastic is recycled, while the global average is approximately 9%. For example, the United States and the European Union have a recycling rate of 34.6% and 31.1%, respectively (UNESCO, 2021). Given this imperative context for circularity tied to production practices, the organizational focus must align on managing post-consumer products and achieving recycling (Vacchi et al., 2021). Civancik-Uslu et al. (2019) point out that to meet the principles of the Circular Economy, Life Cycle Analysis (LCA) represents a strategic tool used to map the impacts throughout the life cycle of a product; and Hurley et al. (2016) complement, highlighting that LCA is the main tool to assess the environmental profile of a product.

In addition, there is a need for a joint effort of different stakeholders in the face of sustainable development. Through the "2030 Agenda for Sustainable Development" an action plan was drawn up, establishing the commitment of government representatives to work unceasingly for the full implementation of the SDGs by 2030, establishing 17 goals to be achieved by that date, such as SDG 9 (Industry, innovation and infrastructure) and SDG 12 (responsible consumption and production). Thus, the need arises for a holistic perspective to achieve the goals, involving mobilization of industry, consumers and government (United Nations General Assembly, 2015).

Based on the above, the objective of this work is to analyze the benefits of the application of recycled polypropylene in the evaporation tray part of refrigerators in a multinational company of electro-electronic equipment. To this end, the methodology applied consisted of: i) conducts a systematic literature review, composed of bibliometric and content analysis; ii) performs a Life Cycle Analysis (LCA) of the production of polypropylene (PP); and iii) presents a case study in a multinational company of white goods electro-electronic equipment (EEE), which proposes the incorporation of recycled polypropylene in a part of the refrigerator: evaporation tray.

2. THEORETICAL REFERENTIAL

2.1 Waste Electrical and Electronic Equipment (WEEE)

Economic development, associated with technological advances, lead to increased use of electro-electronic equipment (EEE) (Panchal, Singh and Diwan, 2021), which represent the segment of greatest contribution to the generation of solid waste (Lu et al., 2022). In view of this, this equipment require special treatment because they usually have large amounts of toxic substances such as lead, mercury, cadmium, chromium, cobalt, polyvinyl chloride (PVC), among others (Nunes et al., 2021; Velásquez-Rodríguez, Løvik and Moreno-Mantilla, 2021).

From this perspective, several laws based on the principle of extended producer responsibility (EPR) have been enacted in recent decades. In the European context, the WEEE directive 2002/96/EC presents the guidelines for the collection, recycling and recovery of electro-electronic waste (WEEE) (Velásquez-Rodríguez, Løvik and Moreno-Mantilla, 2021). In Brazil, the National Solid Waste Policy (PNRS) regulates the production, consumption and disposal of electro-electronic waste according to the Reverse Logistics (Law 12305/10 - art. 33) (BRASIL, 2010). According to Garcia and Benedet (2020), the PNRS applies the principles of Circular Economy to propose the transition from linear production and consumption patterns to a circular perspective, managing balance in the environmental, social and economic spheres.

According to the Brazilian Agency for Industrial Development (ABDI) (2013), electro-electronic equipment is classified into white, brown, blue and green line (Fig. 1). The white line covers large equipment such as refrigerators, washers, dryers, and stoves. The brown line consists of sound and image equipment, such as televisions and monitors. The blue line corresponds to small appliances, such as blenders, coffee makers, mixers, among others.

Finally, the green line covers telephony and computer equipment, such as computers, cell phones, among others (Gomes and Caetano, 2019). Figure 1 shows the characteristics of these categories.

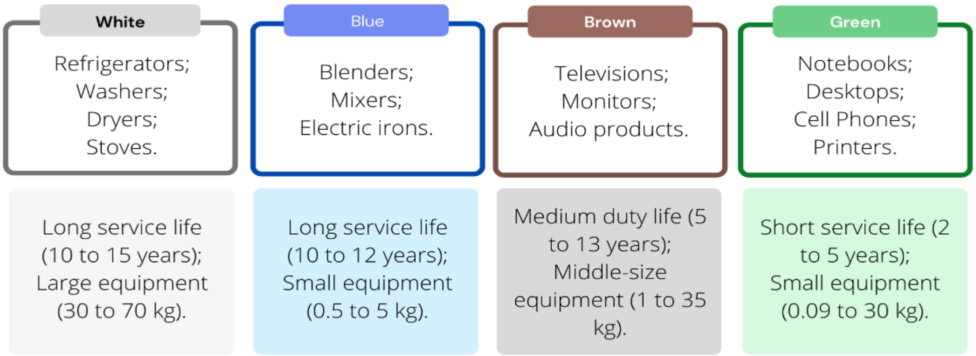

Figure 1 - EEE classification
Source: based on ABDI (2013) and Nunes et al. (2021).

The WEEE recycling system becomes the focus of energy efficiency projects, since they promote the prolonged use of equipment such as refrigerators (Foelster et al., 2016). According to Project Drawdown, 90% of the emissions from refrigerators occur at the end of their useful life, extolling the need to perform proper disposal and reuse of parts and chemicals (Drawdown, 2021). However, Foelster et al. (2016) point out that 71% of Brazilians sell or donate their old refrigerators, and that there is no proper management for the appliances that have been replaced, which are often handled by scavengers or informal collectors of recoverable scrap (Foelster et al., 2016).

Given this context, it becomes essential to incorporate sustainable development principles in the manufacturing and distribution of refrigerators, aiming to mitigate social and environmental degradations, such as the depletion of energy sources and non-renewable resources (Tartibu, 2019). This requires investing in a Reverse Logistics system, making the recycling process feasible (Wang, Hao and Li, 2021). The work of Foelster et al. (2016) quantifies the environmental benefits of a refrigerator recycling scheme in Brazil, and the results point out that the program achieved an average savings of 720 kg of CO2 per refrigerator recycled. Xiao et al. (2016) complements this by highlighting that the main benefits of recycling a refrigerator is the saving of energy and resources such as polymers (high impact polystyrene - HIPS, polypropylene, among others).

2.2 Recycled polypropylene (PP)

Polypropylene (PP) is a thermoplastic polymer of the polyolefin class, considered easy to process (Rodrigues et al., 2017), making it one of the most commercialized polymers (Masson, Oliveira and J, 2021). Its main properties are excellent flexural breaking strength, low weight, high chemical resistance, and great electrical properties. In view of this, PP has a wide application, such as in bumpers, packaging, and appliance housings (William D. Callister, 2008).

Meanwhile, Gökalp (2021) point out that polymers are mechanically tough and difficult to degrade; therefore, their post-use disposal should be based on the Circular Economy (Kohlbeck et al., 2021). Thus, it is necessary to obtain a detailed understanding of the composition and properties of post-consumer materials destined for recycling (Gall et al., 2021). Foelster et al. (2016) point out that when starting the recycling process of a product, such as a refrigerator, easily removable parts should be segregated, such as handles, door seals, iron grids, drawers, glass plates, and plastic parts (Foelster et al., 2016), made predominantly of polypropylene. Given this context, several companies have been committing to reducing their environmental footprint, and polymers have been identified as a critical component of these initiatives in the face of sustainable development (Ladhari et al., 2021).

However, recycled polypropylene has impurity traces, such as the presence of other polymers (e.g. polyethylene, poly ethyl terephthalate - PET and polyamide) (Tratzi et al., 2021), besides presenting lower tensile strength and deformation (Gall, Steinbichler and Lang, 2021). Therefore, it is necessary to perform a classification and determine an ideal percentage for incorporating recycled material in a product (determine the percentage of virgin and recycled material) (Fernandes and Domingues, 2007), analyzing the properties of the samples through tests such as traction, compression, fatigue, shear, hardness, among others (William D. Callister, 2008).

3. METHODOLOGY

This research occurred in three stages, contemplating a mixed approach, since it analyzes bibliographic and empirical data; and employs qualitative and quantitative methods. Figure 2 and the following subsections present the methodological procedures employed in this work.

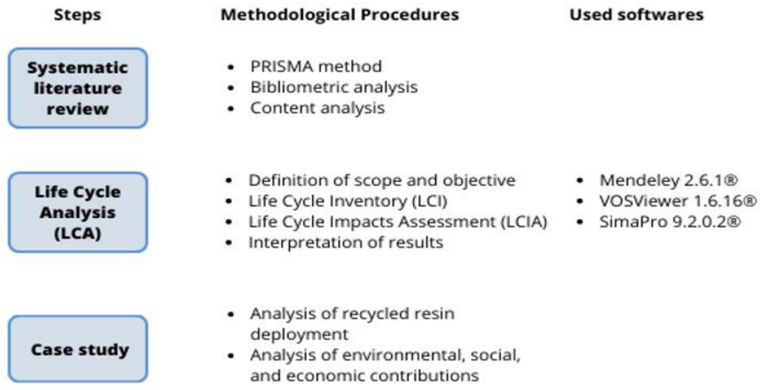

Figure 2 - Methodological procedures
Source: Authors.

3.1 Systematic literature review

A systematic literature review was conducted, aiming to understand the state of the art concerning the topic of this research by synthesizing existing studies. To this end, the report for systematic reviews and meta-analyses (PRISMA) was used to structure this systematic review in four steps: I - identification of studies, II - screening, III - eligibility, and IV - inclusion of papers (Moher et al., 2009); as presented in Figure 3.

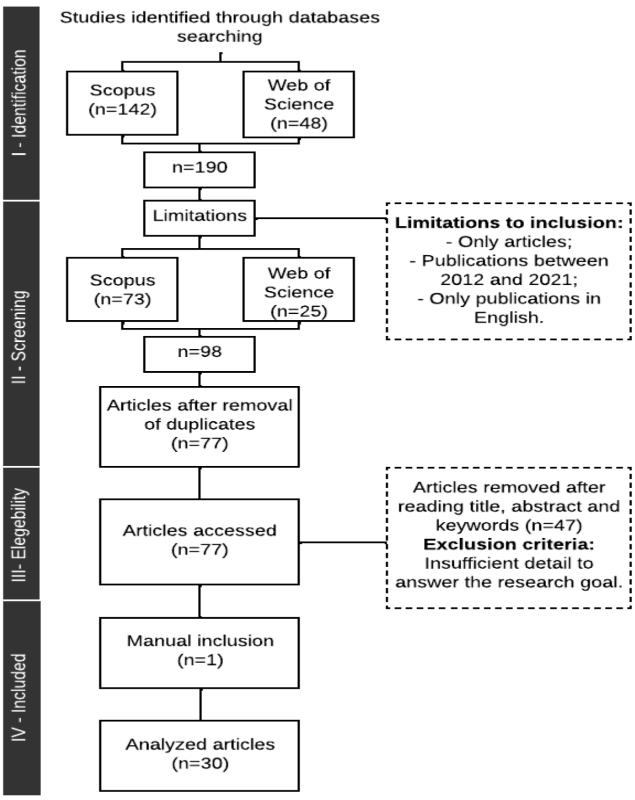

Figure 3 - Prism method - search parameters
Source: Authors.

For the selection of scientific articles, the databases Scopus and Web of Science were used, considered the most comprehensive of the literature (Chadegani et al., 2013). To compose the initial sample of papers to be analyzed, the following combination of keywords was performed: ("white line" OR "refrigerators") AND ("circular economy" OR "sustainability" OR "recycled resin" OR "recycled polymer"), resulting in the identification of 190 works. To further refine the results obtained in step I, a bibliographic search was performed using search filters (phase II), limiting the research to scientific articles published between 2012 and 2021 and written in English. Thus, 98 articles were identified, and for the management of references, the Mendeley® software was used in all stages of this research (Tokarz et al., 2021).

Excluding the duplicates, 77 papers were selected, which composed the bibliometric analyses, presented in section 4.1. According to Zhou and Song (2021), bibliometric analyses make it possible to verify research trends in a quantitative way, through knowledge maps, such as cooperation and co-citation relationships. Bibliographic tools provided by the VOSviewer® and Excel® software were used in the following analyses: temporal trend of publications, main journals, co-citation of authors and geographical distribution of publications. Since VOSviewer® limits the use of only one database, Scopus was used as it presented a greater number of results than Web of Scince (Benachio et al., 2020).

In steps III and IV, title, abstract and keywords of the papers were analyzed. Thus, 30 articles were selected to compose the content analysis, which aims to identify the main approaches to sustainable development that can be applied to the refrigerator market, in order to draw up an action plan for the selected case study. Thus, the content analysis of the systematic literature review supported the development of the research, as well as meeting the general objective.

3.2 Life Cycle Analysis (LCA)

To measure the environmental and human health impacts caused by polypropylene, the Life Cycle Analysis (LCA) tool was used (Pehlken et al., 2014). LCA supports the transition to a Circular Economy (Haupt and Zschokke, 2017), as it represents a systematic approach to quantifying the environmental performance of a product, enabling the identification of solutions to mitigate negative externalities under the environment and to human health (NBR14044, 2006).

To perform the LCA, the software SimaPro® (version 9.2.0.2) was used, which allowed analyzing the life cycle of PP systematically, following the recommendations of the ISO 14040 series (Nunes et al., 2021; SimaPro, 2021). The Ecoinvent 3.7.1 database (Ecoinvent, 2021) was used to develop the life cycle inventory of polypropylene, and the analysis method used was ReCiPe 2016 Midpoint (H).

In 2006, the International Organization for Standardization (ISO) published standards for defining the content and constraints of a Life Cycle Analysis (called ISO 14040) (ABNT, 2006). According to ISO 14040, LCA processes are classified into four steps: (i) Definition of the scope and purpose of the analysis; (ii) Life Cycle Inventory (LCI) (quantitative step that provides the input and output streams for a given process); iii) Life Cycle Impact Assessment (LCIA), where the externalities caused by the system inputs and outputs, the use of raw materials and emissions of pollutants are analyzed; and finally, iv) interpretation of results, in order to compare them with the scope and objective, verifying if they were properly met (ABNT, 2006; Nunes et al., 2021). Figure 4 presents the procedures used to meet the LCA steps.

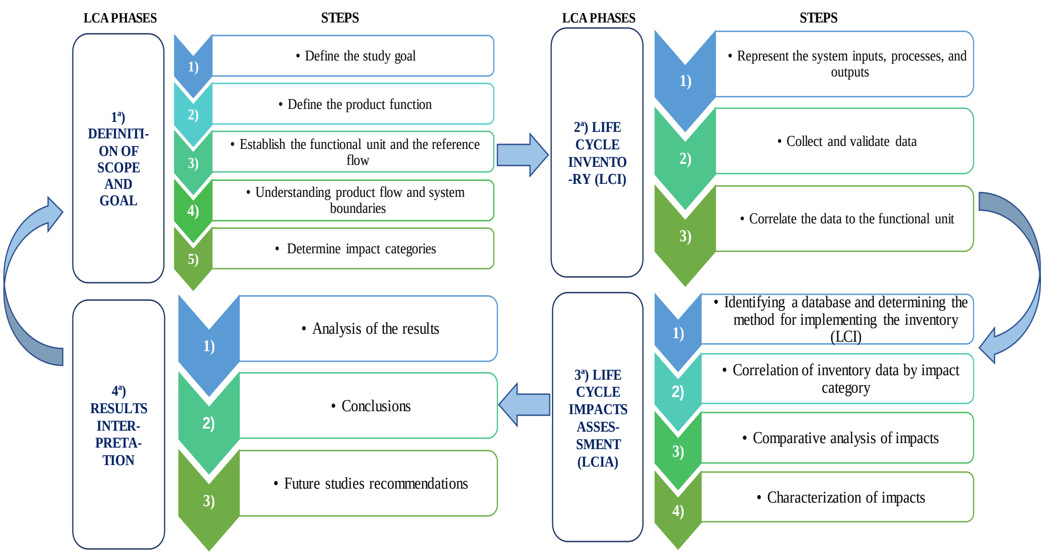

Figure 4 - LCA methodological procedures
Based on: Kohlbeck et al. (2023), NBR14041 (2009), NBR14042 (2009) and NBR14043 (2009).

To analyze the results generated by the software SimaPro®, the data were analyzed using the Pareto Diagram tool, which allowed visualizing which are the variables that generate the greatest impact on polypropylene production. According to Aminmahalati et al. (2021) the Pareto Diagram, associated with simulations, such as those generated by SimaPro®, allow the identification of points for improvement in business proposals, acting in a preventive rather than corrective way.

3.3 Case study

Sarabia et al. (2021) highlight the importance of combining research methods, such as literature reviews and case studies, making it possible to confirm theoretical data and obtain detailed knowledge about a given phenomenon, analyzing issues from different perspectives (Werner et al., 2022). In view of this, this research conducts a case study in a multinational company, a reference in the white goods segment, considered the world's largest manufacturer of home appliances. The studies were conducted at the plant in the city of Joinville, Santa Catarina (Brazil), specialized in the production of refrigerators.

Facing the pressure for corporate strategies capable of leading society toward sustainable development (Julianelli et al., 2020), the company seeks approaches capable of generating a balance between the environmental, social, and economic spheres (Annarelli, Battistella and Nonino, 2020), such as the Circular Economy (Ellen MacArthur Foundation, 2013) and the Sustainable Development Goals (SDGs) by 2030 (United Nations, 2015). In view of this, the company is looking to incorporate recycled resin into its products.

Thus, this research focuses on the implementation of recycled polypropylene in the refrigerator component: evaporation tray (represented in Fig. 5). This part has the function of retaining the defrost water, and is located at the back of the refrigerator, in order to use the heat provided by the compressor to gradually evaporate the water that has accumulated. This part was selected to be worked on for the following reasons: i) the manufacturing material is polypropylene (PP), which has many suppliers capable of providing this recycled resin; ii) it does not represent an aesthetic part, since this property is lower in the recycled material compared to the virgin resin; and iii) wide use of this part, since all the refrigerator models produced have the evaporation tray.

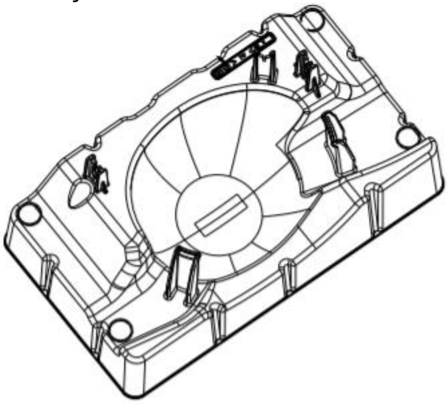

Figure 5 - Technical drawing of the evaporation tray
Source: Authors.

This research advocates the importance of modular design, since in this way there is a reduction in the complexity of assembly and mitigation of premature disposal of the product, increasing its recyclability (Hossain et al., 2021).Thus, given the literature base obtained by the systematic literature review and the measurement of the environmental and human health impacts caused by polypropylene, this work proposes the incorporation of recycled PP in the production of the evaporation tray. In this way, besides increasing the company's alignment with sustainability, there is an increase in competitiveness by proposing a green proposal to the market.

4. RESULTS AND DISCUSSIONS

The first section of this chapter presents the results of the systematic literature review. The following section presents the results of the Life Cycle Analysis (LCA) of the polypropylene, as well as the interpretation of the data through the Pareto Diagram. Finally, the last section contemplates the case study, analyzing the implementation of recycled material in the evaporation container part.

4.1 Systematic literature review

4.1.1 Bibliometric analysis

Figure 6 presents the evolution of scientific production in the period 2012 to 2021. The result shows a growing pattern over the time horizon, especially in 2020 and 2021, since together they represent 32% of the total number of publications. Thus, the trend and academic relevance of this research theme is highlighted.

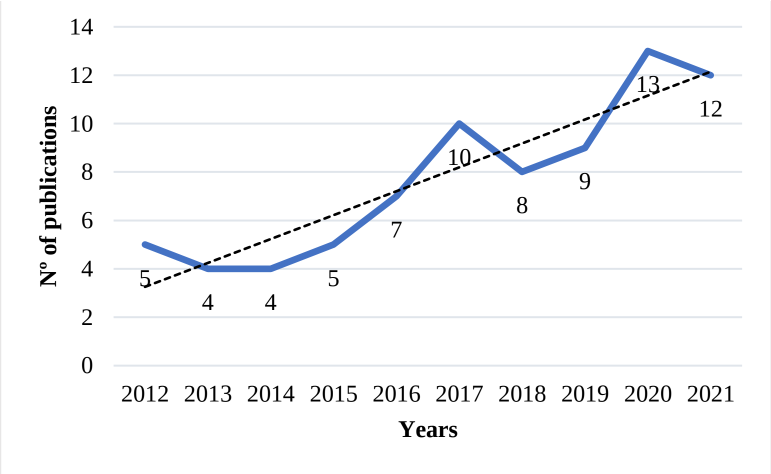

Figure 6 - Temporal trend of publications
Source: Authors.

Fig. 6 highlights a sharp increase in publications from 2017 onwards. This was expected due to the intensification of pressure on sustainable development, especially after 2015, when the SDGs were proposed by the UN. Thus, the results indicate that a mobilization is occurring, from a scientific perspective, facing a restructuring of the current production and consumption patterns. This increase in the number of publications can also be justified by the divulgation of special issues in journals such as the Journal of Cleaner Production and Resources, Conservation and Recycling. Figure 7 corroborates this finding, highlighting that together, these journals represent 14% of the total number of papers that make up the bibliographic portfolio.

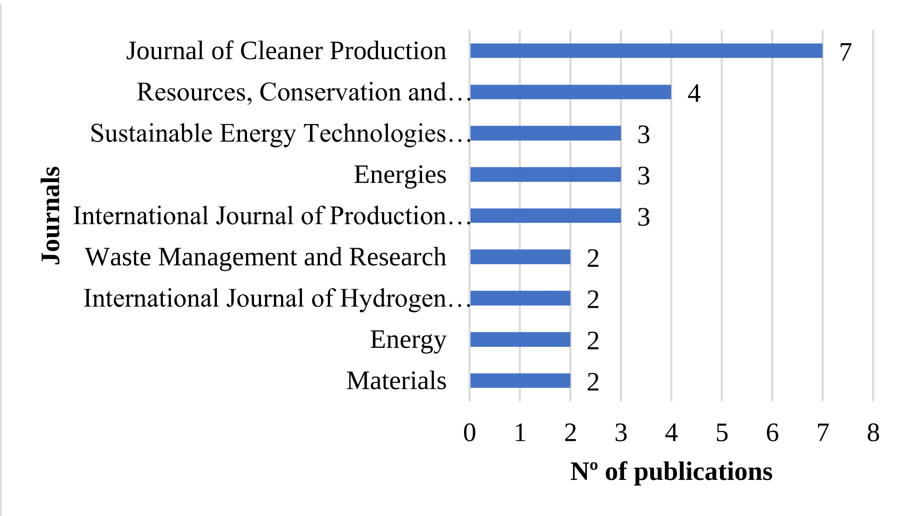

Figure 7 - Main journals
Source: Authors.

Figure 8 shows a co-citation network of authors, where four clusters are formed, giving a bibliometric network consisting of 27 nodes.

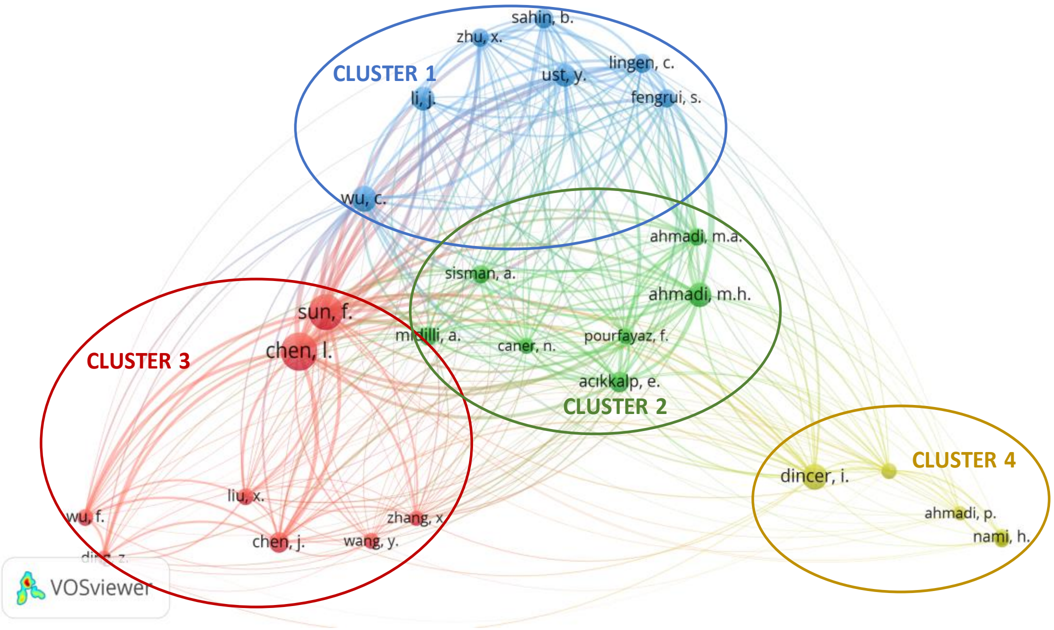

Figure 8 - Author co-citation
Source: Authors.

Wu C. A represents the author with the most publications in cluster 1, with 47 citations. In cluster 2, Ahmadi, M. H. represents the most cited author (n=42). Chen L. and Sun F. (cluster 3) correspond to the most cited authors of the entire analysis, with 102 and 89 citations respectively. Finally, Dicer, I. represents the most cited author in cluster 4 (n=46).

Fig. 9 points out that, although there is a global involvement with the topic of this research, publications are predominantly concentrated in countries with developed economies. China and the United States represent the countries with the most publications, with 11 and 10 papers respectively. Chakraborty et al. (2021) points out that the justification for China's leadership in publication rates may be due to the higher number of funding and/or sponsors for research papers. Retamal (2019) complement by highlighting the need for Research and Development (R&D) investment in all spheres of the economy to mutually meet the goals of sustainable development (Kohlbeck, Beuren, et al., 2021).

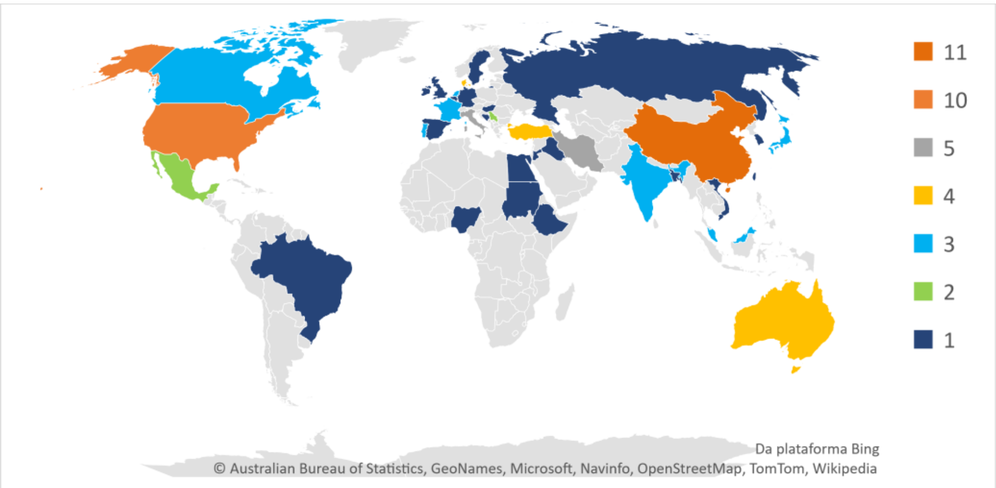

Figure 9 - Geographical distribution of publications
Source: Authors.

4.1.2 Content analysis

Table 1 presents the main bibliographic approaches of the sample analyzed.

Table 1 - Main bibliographic approaches

Main approaches	References	Description
Life Cycle Analysis (LCA)	(Bakker et al., 2014; Xiao et al., 2015; Iraldo, Facheris and Nucci, 2017; Zhang et al., 2019; Hischier and Böni, 2021)	Life Cycle Analysis is an eco-design tool that allows integrating the environmental conditions tied to a product, generating quantitative data capable of guiding the formulation of public policies, marketing strategies, and comparison of different techniques from an environmental perspective (Zhang et al., 2019).
Circular Economy	(Bakker et al., 2014; Iraldo, Facheris and Nucci, 2017; Zhang et al., 2019; Arcos et al., 2020; Denčić-Mihajlov, Krstić and Spasić, 2020; Hischier and Böni, 2021; Mishra, Verma and Tiwari, 2021)	The Circular Economy aims to contribute to the closing of the life cycle of products, aiming for greater durability, resource savings, and waste minimization (Iraldo, Facheris and Nucci, 2017). Its initiatives are receiving public attention in order to pressure global business authorities to meet Circular Economy principles (Hischier and Böni, 2021).
Sustainable design	(Ahamed et al., 2012; Bakker et al., 2014; Xiao et al., 2015; Iraldo, Facheris and Nucci, 2017; Gu et al., 2019; Zhang et al., 2019; Hossain et al., 2021)	Aiming to mitigate negative externalities under the environment (Xiao et al., 2015), sustainable design represents an approach that ensures the eco-design of products by considering all stages of their life cycle (Zhang et al., 2019).
Modularization	(Ahamed et al., 2012; Bakker et al., 2014; Arcos et al., 2020; Hossain et al., 2021)	Modular product design plays a critical role in sustainable product and process development (Hossain et al., 2021), contributing to the implementation of Reverse Logistics (Ahamed et al., 2012).
Recycling	(Fernandes and Domingues, 2007; Bakker et al., 2014; Xiao et al., 2015; Iraldo, Facheris and Nucci, 2017; Denčić-Mihajlov, Krstić and Spasić, 2020; Hischier and Böni, 2021; Hossain et al., 2021)	Operation to recover materials through reprocessing, aiming to maximize their useful life by exploiting the full spectrum of relevant scenarios of a product (Bakker et al., 2014).
Energy efficiency	(Ahamed et al., 2012; Seifi, 2013; Xiao et al., 2015; Ahmadi et al., 2017; Iraldo, Facheris and Nucci, 2017; Duret et al., 2019; Tartibu, 2019; Zha et al., 2020)	In the face of growing emphasis on creating policies that improve energy efficiency and reduce carbon emissions, energy labels are attracting global interest as a means of stimulating the consumption of more energy-efficient products (Xiao et al., 2015; Zha et al., 2020).
Programmed obsolescence	(Bakker et al., 2014; Iraldo, Facheris and Nucci, 2017; Denčić-Mihajlov, Krstić and Spasić, 2020)	Planned obsolescence reduces the useful life of products, making them predisposed to become outdated or stop working after a certain period of use (Bakker et al., 2014; Iraldo, Facheris and Nucci, 2017).

Source: Authors.

Xiao et al. (2015) points out that the refrigerator company entails several negative externalities under the environment, and to mitigate this scenario, it is essential to assess their impacts throughout the life cycle, from the extraction of raw materials to the final disposal of products. Tartibu (2019) adds that in a context of depleting natural resources and concerns about environmental degradation, it is necessary to develop durable and energy-efficient products based on the principles of sustainable development.

To this end, Ma et al. (2018) points out the need for product life cycle management and product design enabling End of Life (EoL) strategies. Thus, the importance of strategic planning is highlighted, since 70% of product cost and 80% of its quality are determined during the product development design stage (Ma, Kremer and Ray, 2018). To this end, it is necessary to measure its impacts from the design phase, where several authors highlight the importance of Life Cycle Analysis (LCA) (e.g. Denčić-Mihajlov et al., 2020; Hischier and Böni, 2021; Iraldo et al., 2017; Xiao et al., 2015) (approach used in this paper and presented in the next sectio).

In this context, Mishra et al. (2021) and Hossain et al. (2021) highlight the importance of design for durability (avoiding planned obsolescence) and of modular design, since they facilitate inspection, maintenance, and repair of products. Thus, the current linear production model is changed to a pattern based on the Circular Economy, meeting the Sustainable Development Goals established by the United Nations (UN) (Hischier and Böni, 2021). To meet these goals, Denčić-Mihajlov et al. (2020) highlight the importance of investing in recycling, especially in the sector of Electrical and Electronic Equipment (EEE). Thus, there is the processing and reuse of used products, reducing harmful effects on the environment and excessive consumption of natural resources; in addition to ensuring a sustainable business future (green marketing) (Denčić-Mihajlov, Krstić and Spasić, 2020).

However, for the reuse system and Reverse Logistics to work, it is necessary that public authorities take specific measures to support the reuse of EEE, which should already have a second-hand market in operation. And here also comes the perspective of the consumer, who becomes an active agent in the operation of the reverse cycle, participating from the Beginning of Life with the selection of purchasing materials aligned with sustainable development, to the End of Life, with the contribution to the correct disposal of materials. Thus, it can be concluded that, in addition to the organizations mobilizing themselves before more sustainable proposals, it is necessary to have an engagement on the part of all the stakeholders.

In a first moment, there is the need to propose alternatives more in line with sustainable development, previously measuring their impacts on the environment and human health, in order to mitigate them beforehand. As the systematic literature review pointed out the contribution of LCA in this context, the next section focuses on the application of this tool to the case study analyzed.

4.2 Life Cycle Analysis (LCA)

Since the literature pointed LCA as a tool aligned with the development of proposals that meet the principles of sustainability, this research conducted the Life Cycle Analysis of PP production. Therefore, Table 2 presents the steps of the 1st phase of LCA (Definition of scope and objective), where the objective of this Life Cycle Analysis is highlighted: to analyze the environmental impacts caused by granulated PP. Thus, this LCA can be used to measure the social and environmental impacts, enabling the identification of alternatives to mitigate them. Table 2 highlights that the study focuses on the production and polymerization phase of polypropylene, considering a production of 1kg of PP.

Table 2 - First step of the LCA - PP production

PHASE	IND	STEPS	CASE STTUDY – PP PRODUCTION
1ª) Definition of scope and objective	1	Determine the objective of the study	Analyze the environmental impacts caused by polypropylene (PP) production
	2	Define the product function	Enable the development of textile products, packaging, household appliances, among others
	3	Establish the functional unit and reference flow	Production of 1kg of Polypropylene
	4	Understand the product flow and system boundaries	This study analyzes the production / polymerization phase of polypropylene
	5	Determine the impact categories	Global warming, stratospheric ozone depletion, ionizing radiation, ozone formation (human health and terrestrial ecosystems), fine particle formation, ozone emission, terrestrial ecosystems, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, human noncarcinogenic toxicity, land use, mineral resource scarcity, fossil resource scarcity, and water consumption

Source: Authors.

In the second and third LCA phase, the SimaPro® software was used, which enabled the construction of the inventory (LCI) (Nunes et al., 2021), representing the inputs, processes and outputs of the polypropylene production, in order to correlate the inventory data with the functional unit (production of 1kg of polypropylene). Next, the life cycle impact assessment (LCA) occurred, which supports the interpretation of an LCA study (Huijbregts et al., 2017). Table 3 presents the main procedures of these steps.

Table 3 - Second and third LCA step - PP production

PHASE	IND	STEPS	CASE STUDY - PP PRODUCTION
2ª) Life Cycle Inventory (LCI)	1	Represent the system inputs, processes, and outputs	SimaPro®
	2	Collect and validate data	
	3	Correlate the data to the functional unit	
3ª) Life Cycle Environmental Impact Assessment (LCIA)	1	Identifying a database and determining the method for implementing the inventory (ICV)	Ecoinvent 3.7.1 and ReCiPe 2016 Midpoint method (H)
	2	Correlation of inventory data by impact category	Figure 10
	3	Comparative analysis of impacts	
	4	Characterization of impacts	Figure 11

Source: Authors.

In the fourth step of LCA, the interpretation of results occurred, so that Figure 10 presents the negative externalities caused by the production of polypropylene. These impacts are presented according to each component used to generate 1 kg of polypropylene, analyzing how they interfere in global warming, in the degradation of the stratospheric ozone layer, in the emission of ionizing radiation, in ozone formation (impacts to human health and terrestrial ecosystems), and in ozone emission, among others.

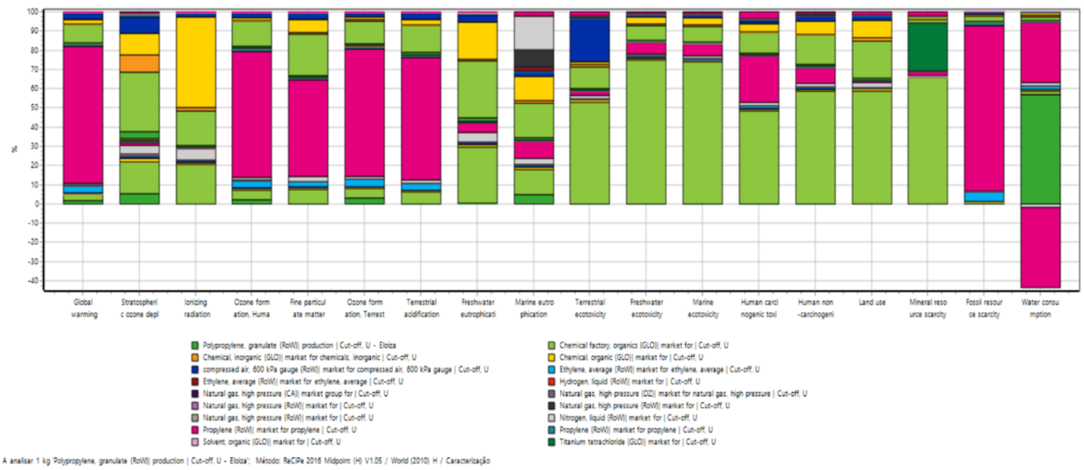

Figure 10 - Impacts of PP production
Source: Authors.

Figure 10 highlights that the propylene component causes several impacts against most of the analyzed categories, especially against global warming (72%), degradation of the ozone layer (66%) and scarcity of fossil resources (86%). These data can be justified by the fact that propylene is a gaseous byproduct of oil refining, and this process represents one of the main sources of industrial carbon dioxide (CO_2) emissions (Cuéllar-Franca and Azapagic, 2015). The Institute of Energy and Environment (IEMA) highlights that global CO_2 emissions had the second largest increase in history in 2021, at 1.5 billion tons (IEMA, 2021). In this context, there is a need to invent recycling and reuse of these petroleum-based compounds, such as propylene (Chen et al., 2022). Figure 11 complements, through a Pareto diagram, that propylene presents the greatest negative externalities on the environment and human health (responsible for 52% of the impacts).

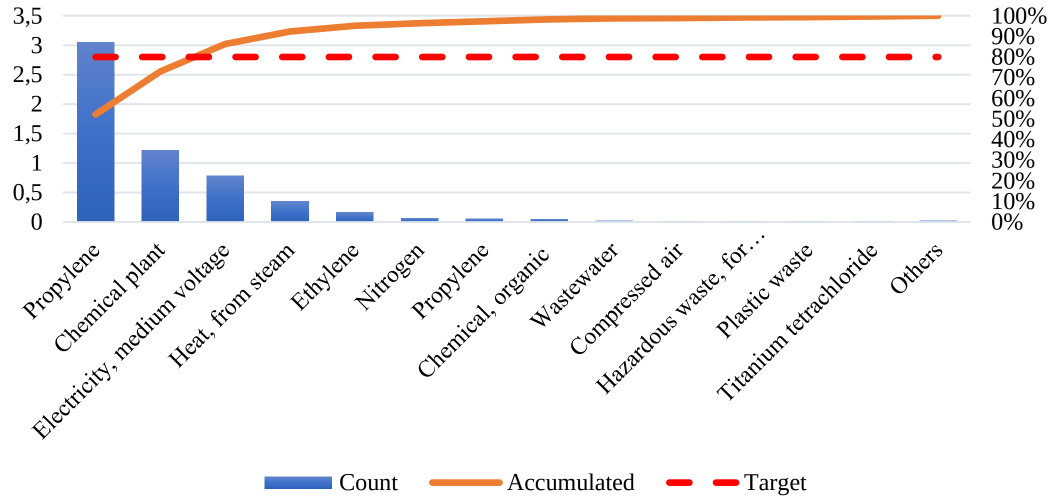

Figure 11 - Variables that generate the greatest impact on PP production
Source: Authors.

Figure 10 and Figure 11 shows that the three main sources of impacts are propylene, the components released by the chemical plant and the impacts caused by electricity consumption. By applying the 80/20 Pareto rule, these variables represent the activities (approximately 20%) responsible for approximately 80% of the impacts, i.e., these are the main factors to develop an action plan to mitigate the negative externalities to the environment and human health caused by the production of polypropylene.

Carere et al. (2021) point out that the chemical industry contributes to the emission of pollutant gases and the imbalance of aquatic ecosystems, representing a problem escalating globally. Fig. 10 shows that the propylene variable has data on both the positive and negative axis of the graph in the "water consumption" dimension, highlighting that this water is used in the process and returned to the environment. However, there is a need to perform its treatment, since the graph points out impacts in the dimensions "marine eutrophication" and "marine ecosystem".

In order to mitigate the main negative externalities caused by the production of polypropylene, especially the impacts caused by propylene, by the chemical plant, and by the expense with electricity (responsible for approximately 80% of the impacts), the following section presents a case study, where the recycling of polypropylene is analyzed, in order to reinsert it in the productive cycle of the evaporation container product, using Circular Economy principles as a basis.

4.3 Case study: Implementation of recycled material

Given the bibliographical foundation and the Life Cycle Analysis (LCA), the importance of recycling polypropylene was proven, in order to increase its contribution, avoiding disposal in landfills while it still has productive potential. In view of this, Fig. 12 shows the flow of polypropylene for production of the evaporation container, considering the principles of Circular Economy and Sustainable Development Goals, since the proposal is aligned with SDG 9 (industry, innovation, and infrastructure) and SDG 12 (responsible consumption and production).

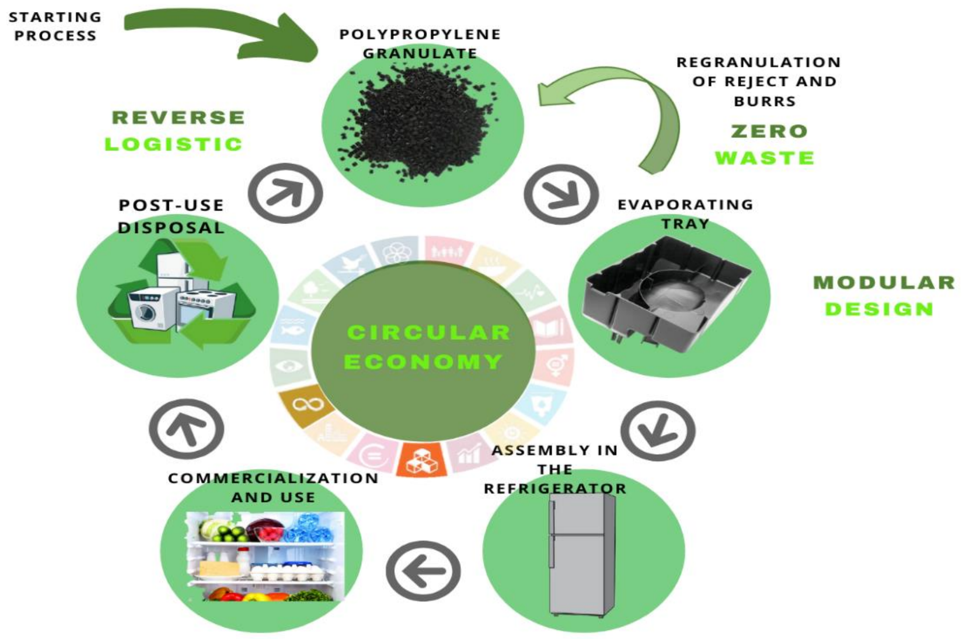

Figure 12 - PP Cycle based on sustainability
Source: Authors.

Figure 12 highlights that the proposal meets the concept of zero waste, since the maximum utilization during the production process, both of rejected parts by quality criteria, as well as the PP injection burrs, which are regranulated through a mill present in the company. Furthermore, the importance of modular design is emphasized, so that each part that makes up a product must be designed with sustainable development in mind. Das and Rao Posinasetti (2015) point out that modularity contributes to flexibility in the reuse of components, facilitating assembly and disassembly.

After the product is sold and used, the refrigerator is sent for final disposal, and through a Reverse Logistics system, the used product is collected and sent to a company specializing in polypropylene recycling. Next, regranulation and tests are performed to identify the ideal composition of virgin PP, recycled PP, and regranulated PP. Thus, the aspects highlighted in Table 4 were analyzed to meet the technical and commercial requirements of the incorporation of recycled PP in the evaporation container part.

Table 4 - Technical and commercial strategy

Ind	Analysis
1	Identification of suppliers that have a competitive (saving) commercial proposal
2	Supplier's willingness to meet chiller production demand
3	Supplier's technical capability
4	Analysis of the supplier's engagement (mission, vision and values) with sustainable development
5	Identification of the ideal formulation in relation to the composition of virgin, regranulated and recycled material
6	Analysis of the results under environmental, social, and economic aspects

Source: Authors.

First, the supplier was selected that was able to i) provide a competitive price for the recycled material; ii) meet the refrigerator production demand; iii) have service capability and iv) be aligned with the mission, vision and values of the company, meeting the principles of sustainable development. These criteria were used for supplier selection, in order to select the one most aligned with the four criteria.

After the identification of the supplier most technically and commercially aligned with the proposal, the contribution to the following scopes is observed:

I. Environmental, due to the engagement with the Circular Economy, Sustainable Development Goals (SDGs), modular design, and the Zero Waste policy.
II. Social, since it represents a measure aligned with the improvement of quality of life, by contributing to the reduction of the Environmental Footprint.

III. Economic, since the quotation with suppliers highlighted a discount percentage of up to 9.5% on recycled PP.

In addition to the contribution to the Triple Bottom Line, there is an advantage for the case study company, since there is a projection of increased sales when proposing a product containing parts with recycled material, and the supplier is increasingly valuing proposals aligned with sustainable development. In addition, the cost reduction provided by the partner supplier allows the price of the final product to remain competitive, increasing the chances of sales.

5. CONCLUSIONS

This work aimed to analyze the benefits of the application of recycled polypropylene in the evaporation tray part of refrigerators in a multinational company of electro-electronic equipment. The systematic literature review performed pointed out trends under this imperative perspective for sustainable development practices, among them recycling, modularization and Life Cycle Analysis (LCA). In view of this bibliographical foundation, this work pointed out the negative externalities caused by the production of polypropylene, where the potential of recycling to mitigate the impacts of PP on the environment and human health stands out.

Thus, through the case study, its possible to conclude that practices such as recycling, besides contributing to sustainable development, represent an opportunity for market differentiation, intensifying competitiveness in the Business to Business (B2B) and Business to Consumer (B2C) models (green marketing).

The case study pointed out a contribution under the three scopes of the Triple Bottom Line (environmental, social and economic), since the proposal proved to be economically attractive, besides presenting benefits capable of mitigating the environmental and social impacts pointed out by the LCA. This study also contributes to a possible increase in refrigerator sales because of two factors: i) the price will remain competitive, ii) products aligned with sustainable development are being demanded by consumers. Thus, the company will invest in green marketing in order to publicize the work developed.

Therefore, the research presents a methodological value for reconciling quantitative and qualitative methods, and a practical and empirical approach. The theoretical part was the basis for the development of an action plan to make the transition to a proposal more aligned with sustainability. Thus, this research represents the first step towards the application of recycled material in the refrigerators of the multinational company analyzed, where it seeks to expand the use of recycled PP in other parts besides the evaporation tray.

Finally, it is highlighted that the methodology used in this work can be used for the expansion in other products of a refrigerator, aiming the modular design, or of products from other segments. Thus, future studies can focus on this expansion of the scope of this work, and on the application of other methods and tools, in addition to Life Cycle Analysis, capable of guiding and measuring the contributions of the recycling system.

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